In accordance with a preferred embodiment of the present invention the plurality of sub-channels may be created by splitting a laser output of a laser by an optical splitter. The optical information may be modulated externally with an external modulator.

## BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood and appreciated more fully from the following detailed description taken in conjunction with the appended drawings in which:

Fig. 1 is a simplified block diagram illustration of a system and method for frequency division multiplexing of optical signals, in accordance with a preferred embodiment of the present invention;

Fig. 2 is a simplified block diagram illustration of resonant frequency division multiplexing of optical signals, in accordance with a preferred embodiment of the present invention; and

Fig. 3 is a simplified block diagram illustration of alternative embodiments of the present invention, wherein the individual laser power of one laser may be split into a number of channels by an optical splitter, and data may be modulated externally.

## DETAILED DESCRIPTION OF THE PRESENT INVENTION

Reference is now made to Fig. 1, which illustrates an optical communication system 10 that employs frequency division multiplexing of optical signals, in accordance with a preferred embodiment of the present invention.

System 10 is preferably a WDM system that employs a plurality of laser groups 12, each of which may receive a modulated input signal. (However, it is appreciated that the invention may also be carried out for any carrier of optical information, even a single fiber.) A preferred laser is a diode laser, but the invention is not restricted to diode lasers and the skilled artisan will appreciate that the invention may be carried out with other kinds of lasers as well. Each laser group 12 outputs an optical signal channel to which is assigned a particular channel wavelength $\lambda_i$ (e.g., $\lambda_1, \lambda_2, \ldots \lambda_n$).

In accordance with a preferred embodiment of the present invention, at least one, and preferably all, wavelengths $\lambda_i$ ($\lambda_1, \lambda_2, \ldots \lambda_n$) are modulated by frequency division multiplexing. This is preferably accomplished by sub-dividing each laser group 12 into a plurality of sub-channels 22 ($\lambda_{11}, \lambda_{12}, \ldots \lambda_{1m}, \lambda_{21}, \lambda_{22}, \ldots \lambda_{nm}$) on the particular wavelength $\lambda_i$ of the WDM carrier, each sub-channel 22 with its own data information being created by a laser 23. Each individual sub-channel 22 is then preferably up-converted with an optical up-conversion unit 24. (It is noted that optical up-conversion unit 24 is illustrated as one block in Fig. 1, but in reality preferably up-converts each sub-channel 22 individually, as mentioned before.)

Alternatively, as seen in Fig. 3, the individual laser power of one laser 23 may be split into a number of channels by an optical splitter 17 instead of using individual lasers for each sub-channel 22. As another option, laser 23 may be a continuous wave (CW) laser and the data may be modulated externally, such as by means of an external electro-optical intensity modulator 19. The optical up-conversion methods of the invention enable transmitting sub-channels wherein each sub-channel may carry a different amount of information, and may have different bandwidth size. This capability allows flexibility of remote bandwidth control.

Reference is now made to Fig. 2. In accordance with one embodiment of the present invention, optical up-conversion unit 24 comprises a resonant electro-optical modulator 26. By way of example only, in the illustrated embodiment there are 16 lasers 23 for each color (wavelength $\lambda_i$). Resonant electro-optical modulator 26 may comprise arrays of oscillating crystals 28, such as two arrays of 4 crystals with resonant

frequencies $f_{11}$, $f_{12}$, $f_{13}$ and $f_{14}$, and $f_{21}$, $f_{22}$, $f_{23}$ and $f_{24}$ respectively. Resonant electro-optical modulator 26 up-converts the input wavelength $\lambda_i$ into 16 sub-channels 22 operating at frequencies $f_{11}+f_{21}$, $f_{11}+f_{22}$, $f_{11}+f_{23}$, $f_{11}+f_{24}$, $f_{12}+f_{21}$, ... $f_{14}+f_{24}$. Another possible implementation is to arrange the crystals as a one dimensional array comprising 16 (but not limited to 16) crystals each resonating at its particular resonant frequency.

The skilled artisan will appreciate that each sub-channel 22 may be optically up-conversed in the arrangement of Fig. 3, by connecting the external data modulator 19 to an up-converter that is an electro-optical modulator operating at the resonant frequency f1 corresponding to channel $\lambda_{11}$. The second sub-channel $\lambda_{12}$ may be connected to another electro-optical modulator operating at the resonant frequency f2 and so forth.

The term resonant electro-optic modulator, as used herein, refers to any resonant electro-optical modulator without distinction as to which stage of the up conversion system the resonant effect takes place. The resonant electro-optic modulator may be a resonant electrical source (e.g., Gunn diode or equivalent), a resonant electrical filter, a resonant wave guide cavity or a resonant optical component (e.g., Fabry-Perot, Etalon or equivalent). The term electro-optical modulator refers to a device that modulates light at a given frequency under oscillatory conditions.

In accordance with the present invention, resonant electro-optical modulator 26 may modulate the optical signals with its data content by means of a radio-frequency (RF) signal modulated by an electromagnetic field according to well-known principles of electro-optics. In accordance with one embodiment of the present invention, each sub-channel 22 operates at a relatively low central frequency, typically, but not necessarily, below 5 GHz, preferably around 1 GHz. It is noted that the invention is not limited to these values. Optical up-conversion unit 24 preferably up-converts the optical information in the frequency domain with a different carrier frequency. The different carrier frequencies may be separated from each other, for example, but not limited to, by about 2 GHz, depending on the information bandwidth. Such an up-conversion may attain carrier frequencies per individual WDM laser approaching 70-80 GHz and higher, as mentioned previously, a significant improvement over the prior art.

Reference is again made to Fig. 1. A multiplexer 14 multiplexes the optical signals channels emanating from optical up-conversion units 24 to form an optical signal comprising the individual optical signal channels, which is transmitted over a single optical waveguide 16, such as an optical fiber. A demultiplexer 18 demultiplexes the

optical signal such that each channel wavelength $\lambda_i$ ($\lambda_1$, $\lambda_2$, ... $\lambda_n$) is individually routed to a designated receiver 20.

In contrast to the prior art, in the present invention it is possible to add or drop channels at any point along the optical transmission line while still in the optical domain. This may be achieved by down-converting the optical signals with an optical down-conversion unit 30 in the frequency space, in a format or protocol compatible with optical up-conversion unit 24. Optical down-conversion unit 30 may comprise the same type of resonant electro-optical modulator as optical up-conversion unit 24. Individual outputs of the optical down-conversion unit 30 are individually routed to designated receivers 20 (receivers 1, 2, ... n in Fig. 1). Optical to electrical (O/E) conversion may be performed at receivers 20 comprising, but not limited to, an O/E conversion unit 31, such as a photodiode, and an electrical band pass filter 32. Only the appropriate matched down conversion frequency is processed by the appropriate receiver 20.

The capacity to add and drop small channels, wherein the address of the customer is programmed at the source site by choosing a carrier frequency, opens many new avenues in routing and control of networks. This scheme may be described as "remote bandwidth control", or a "virtual back plane" wherein a physical back plane is replaced by logical controls. For example, at a central station, management can allocate or decide how much, where and which user will get the appropriate bandwidth and capacity (e.g., offices, campuses, homes, etc. depending on the working hours and the like).

In the present invention, the amount of data transmitted in one WDM channel may be increased by a factor of 2-3, while lowering the operating frequency of the associated electronics, detectors and lasers (by at least a factor of 5-10). The amount of data processed for each channel is much lower in comparison to the prior art, and there is no need to process the entire data in order to receive an individual group or channel. The methods of the present invention may be implemented separately at each WDM channel. The problems of fiber effects, including inter alia, dispersion and non-linear effects, are substantially reduced, thereby significantly increasing the attainable transmission length before any signal regeneration is required for extending the transmission length.

It will be appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and described herein above. Rather the scope of the invention is defined by the claims that follow: